NASA MEMO 1-10-59E

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PRESSURE DRAG OF AXISYMMETRIC COWLS HAVING LARGE INITIAL LIP ANGLES AT MACH NUMBERS FROM 1.90 TO 4.90

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Lewis Research Center
Cleveland, Ohio

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SUMMARY

The results of experimental and theoretical data on nine cowls are presented to determine the effect of initial lip angle and projected frontal area on the cowl pressure drag coefficient at Mach numbers from 1.90 to 4.90. The experimental drag coefficients were approximated well with two-dimensional shock-expansion theory at the lower cowl-projected areas, but the difference between theory and experiment increased as the cowl area ratio was increased or as shock detachment at the cowl lips was approached. An empirical chart is presented, which can be used to estimate the cowl pressure drag coefficient of cowls approaching an elliptic contour.

INTRODUCTIONS

Evaluation of cowl designs for high-speed flight is a necessary part of a preliminary performance analysis. Several theoretical approaches are available that give satisfactory agreement with experimental pressure-drag data on unity-mass-flow-ratio cowls for various combinations of contours and flow conditions. For example, the linearized source distribution method gives satisfactory results for slender bodies at moderate supersonic speeds, but the error increases with either increasing Mach number or increasing surface angle (refs. 1 and 2). Van Dyke's second-order supersonic flow calculations are limited to contours with maximum slopes less than $0.94\ (M^2 - 1)^{-1/2}$ (where M is Mach number), which corresponds to surface angles of approximately 28°, 18°, and 13° at Mach numbers of 2, 3, and 4, respectively (ref. 3). two-dimensional shock-expansion method (refs. 4 to 6) neglects the three-dimensional effect and the reflection of disturbances originating at the surface, which introduces only small errors except at large lip angles (near shock-detachment values). Another possible way to predict cowl drags theoretically is with the use of the method of characteristics, but this solution is quite tedious and time consuming and requires modifications when detached shock waves exist (ref. 7). A review of various existing theories appears to indicate a definite need for empirical cowl-pressure-drag data in the area of lip angles near shock-detachment values, where most of the methods yield the greatest deviations from the exact values.

In view of the items discussed previously and the lack of sufficient experimental data, a wind-tunnel test program was initiated at the NACA Lewis laboratory. An investigation of existing cowl designs indicated that an elliptic contour closely approximated the majority of shapes examined. A family of nine elliptically contoured cowls was designed, therefore, which incorporated large initial lip angles and various projected areas. Measured cowl pressure drags in the Mach 2.0 to 5.0 range were compared with values obtained with two-dimensional shock-expansion theory. This theory was chosen because it is readily adaptable to preliminary-type analysis calculations.

APPARATUS

The contours from the lip to the maximum 6-inch-diameter section (fig. 1) of the steel models were defined by portions of ellipses, which were tangent at the semiminor axis to the constant diameter portion of the cowls. The aspect ratio of the ellipses was varied to give initial nominal lip angles of 20°, 28°, and 34° with projected areas of 20, 35, and 50 percent of the maximum frontal area. The final cowl coordinates x and y_r of the family of cowls tested are listed in table I. Static-pressure orifices were located externally on the cowls at longitudinal positions from 0.060 inch aft of the lip to the constant-diameter section. The internal contour of the cowls was a straight diverging taper from the cowl lip to the cowl exit. All of the cowls had sharp lips with maximum radii of 0.0025 inch. Scaled drawings of the external contours are shown in figure 1 and photographs of three typical models are presented in figure 2. The models were strut supported and tested in several of the Lewis laboratory small supersonic wind tunnels at zero angle of attack. The Reynolds number was held relatively constant at each Mach number and had values of 5.2×10^6, 6.1×10^6, 4.9×10^6, 1.1×10^6, and 4.4×10^6 per foot at the respective free-stream Mach numbers of 1.98, 2.47, 2.94, 3.88, and 4.90.

RESULTS AND DISCUSSION

The experimental surface pressure coefficients are listed as a function of axial distance from the lip in table II. Figure 3 is a representative plot showing the longitudinal pressure distribution for both the experimental and theoretical results of the 34° initial lip angle cowls at a Mach number of 3.88. The experimental pressure distributions are closely approximated by shock-expansion theory at the smaller projected areas but deviate progressively as the projected cowl areas are increased.

The experimental pressures were integrated over the cowl surfaces and the resultant drag coefficients, based on the maximum cross-sectional area, were compared with values calculated using two-dimensional shock-expansion theory in all cases where attached shock waves existed. No attempt was made to calculate theoretical drag coefficients when detached waves existed at the cowl lip, but estimates can be made with the aid of reference 8.

Figures 4, 5, and 6 show the effects of lip angle, projected cowl area, and Mach number on the cowl pressure drag coefficients. The theoretical results are shown only for attached-shock conditions at the lip. While the empirical data are approximated rather well with shock-expansion theory at the lower projected cowl areas, the deviation between theory and experiment became increasingly greater as the area ratio was increased. This deviation with increasing area ratio can be attributed to the greater variation in radius (a larger three-dimensional effect). In several instances, the theoretical results indicated a rather sharp rise in drag as the shock-detachment value was approached at the lip, but the experimental data, in general, revealed no abrupt changes when theoretical shock detachment had been attained at the lip. The cowl family tested maintained the initial lip angle for only a small distance (less than 0.1 in.), which caused only a small portion of the cowl-lip shock wave to detach at the predicted shock-detachment Mach numbers. This detail can be seen in the schlieren photographs in figure 7 where shock detachment at the lip was not apparent until Mach numbers substantially lower than theoretically predicted (Mach 2.95) had been reached.

Although no data are presented, several of the cowls were investigated at two Reynolds numbers at Mach 2.94. A small effect was noted, which resulted in drag coefficients 3 to 5 percent higher for the cowls tested at a Reynolds number of 2.5×10^6 as compared with those tested at 4.9×10^6 per foot.

The experimental data are combined in figure 8 as an empirical chart for use in estimating the cowl-pressure-drag coefficient of cowls approximating or having an elliptic external contour. The use of the chart is illustrated by the arrows in figure 8. For example, the cowl pressure drag coefficient at Mach 3.4 of an elliptically contoured cowl, having a cowl projected area which is 20 percent of the total frontal area and an initial lip angle of 34°, is approximately 0.096.

CONCLUDING REMARKS

The cowl pressure drag coefficients were approximated well with two-dimensional shock-expansion theory at the lower projected cowl areas, but the deviation between theory and experiment increased as the projected cowl area ratio was increased or as shock detachment at the cowl lip was approached. An empirical chart was developed from the experimental data for estimating the pressure drags of cowls having or approximating elliptic external contours.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 4, 1958

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2. Jack, John R.: Theoretical Wave Drags and Pressure Distributions for Axially Symmetric Open-Nose Bodies. NACA TN 2115, 1950.

3. Van Dyke, Milton D.: Practical Calculation of Second-Order Supersonic Flow Past Nonlifting Bodies of Revolution. NACA TN 2744, 1952.

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5. Syvertson, Clarence A., and Dennis, David H.: A Second-Order Shock-Expansion Method Applicable to Bodies of Revolution Near Zero Lift. NACA Rep. 1328, 1957. (Supersedes NACA TN 3527.)

6. Eggers, A. J., Jr., and Savin, Raymond C.: Approximate Methods for Calculating the Flow About Nonlifting Bodies of Revolution at High Supersonic Airspeeds. NACA TN 2579, 1951.

7. Ferri, Antonio: Application of the Method of Characteristics to Supersonic Rotational Flow. NACA Rep. 841, 1946. (Supersedes NACA TN 1135.)

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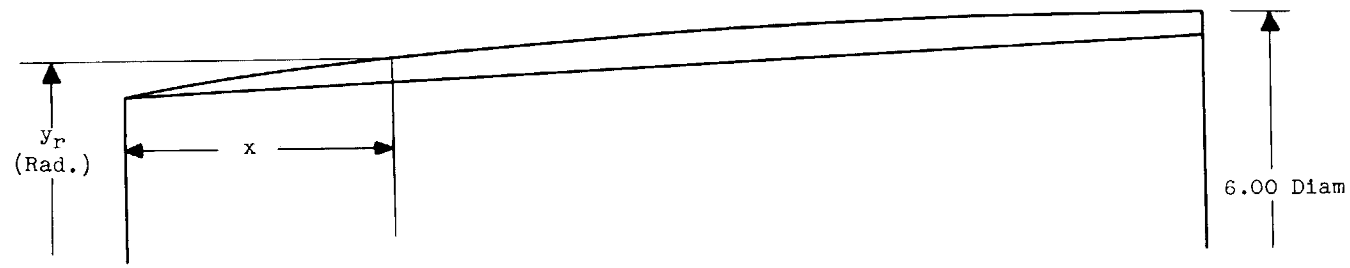
TABLE I. - COWL COORDINATES

[All dimensions in inches.]



Cowl 1		Cowl 2		Cowl 3		Cowl 4		Cowl 5		Cowl 6		Cowl 7		Cowl 8		Cowl 9	
x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r
0	2.685	0	2.420	0	2.124	0	2.685	0	2.420	0	2.124	0	2.685	0	2.420	0	2.124
.10	2.712	.10	2.447	.10	2.151	.10	2.732	.10	2.467	.10	2.171	.10	2.750	.10	2.488	.10	2.192
.20	2.740	.20	2.473	.20	2.178	.20	2.775	.20	2.510	.20	2.217	.20	2.794	.20	2.542	.20	2.250
.40	2.782	.40	2.520	.40	2.230	.30	2.809	.30	2.553	.40	2.300	.30	2.833	.30	2.598	.40	2.359
.60	2.822	.60	2.570	.60	2.280	.40	2.843	.40	2.592	.60	2.380	.40	2.870	.40	2.648	.60	2.452
.80	2.859	.80	2.615	.80	2.330	.50	2.863	.60	2.665	.80	2.453	.60	2.924	.60	2.720	.80	2.534
1.00	2.891	1.00	2.653	1.00	2.377	.60	2.896	.80	2.735	1.00	2.518	.80	2.962	.80	2.792	1.00	2.606
1.20	2.917	1.20	2.700	1.20	2.430	.80	2.937	1.00	2.785	1.20	2.579	1.00	2.985	1.00	2.843	1.20	2.670
1.50	2.951	1.50	2.754	1.50	2.483	1.00	2.967	1.20	2.830	1.50	2.660	1.20	2.997	1.20	2.890	1.50	2.752
2.00	2.985	2.00	2.831	2.00	2.580	1.20	2.988	1.50	2.884	2.00	2.772	1.305	3.000	1.50	2.937	2.00	2.860
2.47	3.000	2.50	2.892	2.50	2.663	1.50	2.998	2.00	2.953	2.50	2.859			2.00	2.989	2.50	2.934
		3.00	2.940	3.00	2.738	1.57	3.000	2.50	2.991	3.00	2.923			2.40	3.000	3.00	2.980
		3.50	2.974	3.50	2.805			2.89	3.000	3.50	2.966					3.50	2.990
		4.00	2.995	4.00	2.857					4.00	2.989					3.63	3.000
		4.50	2.999	4.50	2.902					4.36	3.000						
		4.56	3.000	5.00	2.941												
				5.50	2.968												
				6.00	2.990												
				6.50	2.999												
				6.90	3.000												

TABLE II. - EXPERIMENTAL PRESSURE DISTRIBUTIONS

Cowl 1

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.98	2.47	2.94	3.88	4.90
0.07	0.510	0.400	0.345	0.312	0.276
.11	.468	.366	.315	.276	.246
.16	.401	.320	.267	.242	.244
.21	.368	.290	.232	.229	.205
.28	.364	.285	.224	.198	.187
.36	.315	.248	.208	.172	.169
.44	.276	.223	.160	.162	.157
.54	.258	.203	.157	.155	.145
.64	.256	.208	.166	.140	.133
.76	.224	.180	.153	.127	.121
.90	.197	.162	.126	.114	.109
1.05	.167	.134	.103	.103	.097
1.20	.152	.127	.103	.088	.085
1.36	.118	.097	.084	.071	.073
1.55	.090	.071	.052	.060	.055
1.90	.034	.030	.025	.032	.025
2.40	-.008	-.003	.002	.006	.014

Cowl 2

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.98	2.47	2.94	3.88	4.90
0.07	0.506	0.413	0.350	0.323	0.294
.11	.456	.351	.292	.271	.246
.16	.425	.337	.298	.249	.235
.20	.421	.335	.291	.247	.223
.30	.387	.318	.261	.229	.217
.38	.370	.296	.257	.215	.205
.48	.340	.287	.253	.200	.191
.60	.337	.277	.231	.197	.181
.74	.312	.250	.203	.181	.169
.89	.280	.233	.195	.165	.157
1.08	.257	.215	.186	.152	.145
1.30	.233	.197	.165	.136	.127
1.55	.187	.156	.125	.114	.109
1.90	.145	.124	.101	.090	.091
2.25	.104	.089	.082	.069	.067
2.60	.087	.076	.070	.058	.055
2.95	.071	.056	.050	.049	.049
3.30	.037	.030	.028	.029	.035
3.70	.008	.013	.008	.016	.025
4.50	-.032	-.015	-.011	-.004	.007

Cowl 3

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.98	2.47	2.94	3.88	4.90
0.08	0.576	0.459	0.398	0.325	0.304
.12	.503	.380	.328	.289	.262
.16	.468	.358	.309	.274	.244
.22	.436	.337	.295	.251	.226
.30	.435	.340	.309	.247	.238
.40	.410	.326	.279	.238	.226
.52	.381	.310	.267	.228	.214
.66	.362	.283	.247	.208	.196
.80	.342	.277	.241	.198	.191
.98	.315	.251	.217	.185	.17[illegible]
1.18	.271	.221	.193	.164	.155
1.40	.236	.189	.168	.139	.131
1.65	.210	.173	.155	.126	.119
1.90	.184	.157	.133	.113	.107
2.20	.163	.140	.120	.100	.098
2.50	.154	.131	.117	.093	.095
2.75	.144	.126	.112	.088	.089
3.25	.111	.097	.079	.072	.071
3.75	.064	.056	.044	.047	.065
4.25	.065	.042	.036	.037	.042
4.75	.034	.036	.028	.027	.035
5.25	.022	.018	.012	.021	.030
6.00	-.014	-.013	-.010	.004	.012
6.75	-.035	-.030	-.024	-.011	.000

Cowl 4

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.98	2.47	2.94	3.88	4.90
0.08	0.861	0.685	0.605	0.522	0.485
.11	.755	.610	.529	.446	.413
.15	.675	.537	.459	.412	.377
.21	.622	.503	.408	.381	.342
.28	.594	.481	.427	.361	.330
.35	.532	.449	.397	.326	.306
.43	.471	.399	.338	.299	.282
.53	.387	.324	.262	.247	.223
.64	.320	.279	.244	.203	.193
.76	.236	.195	.176	.154	.139
.90	.191	.163	.133	.128	.115
1.05	.135	.115	.090	.095	.082
1.20	.082	.078	.063	.062	.062
1.35	.013	.024	.023	.029	.032
1.50	-.003	.006	.004	.019	.026

Cowl 5

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.98	2.47	2.94	3.88	4.90
0.08	0.914	0.756	0.693	0.56[illegible]	0.534
.12	.810	.645	.621	.49[illegible]	.474
.16	.751	.595	.551	.46[illegible]	.438
.22	.723	.582	.508	.44[illegible]	.420
.28	.716	.592	.557	.44[illegible]	.418
.36	.675	.563	.534	.41[illegible]	.408
.44	.619	.529	.490	.40[illegible]	.391
.54	.568	.485	.443	.37[illegible]	.355
.64	.504	.437	.418	.33[illegible]	.319
.76	.414	.362	.349	.27[illegible]	.271
.90	.310	.273	.256	.22[illegible]	.211
1.04	.251	.220	.207	.18[illegible]	.176
1.20	.216	.201	.193	.15[illegible]	.146
1.36	.178	.160	.164	.12[illegible]	.128
1.54	.146	.135	.124	.10[illegible]	.104
1.90	.094	.090	.089	.07[illegible]	.080
2.35	.021	.034	.046	.03[illegible]	.044
2.80	-.034	-.014	-.001	.00[illegible]	.020

Cowl 6

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.90	2.47	2.94	3.88	4.90
0.08	0.953	0.743	0.645	0.564	0.523
.12	.924	.711	.606	.538	.505
.16	.845	.660	.584	.508	.482
.22	.773	.642	.554	.492	.458
.30	.732	.629	.559	.475	.452
.38	.661	.588	.515	.453	.434
.50	.585	.530	.461	.407	.392
.74	.464	.436	.391	.336	.390
.90	.394	.382	.325	.293	.314
					.278
1.08	.336	.331	.284	.255	.242
1.30	.288	.290	.257	.227	.212
1.55	.238	.246	.221	.194	.182
1.90	.172	.189	.160	.151	.146
2.25	.102	.138	.118	.111	.110
2.60	.064	.103	.089	.087	.086
2.95	.031	.068	.058	.065	.068
3.30	-.012	.037	.036	.041	.059
3.70	-.053	.008	.009	.025	.032
4.30	-.079	-.014	-.011	.008	.015

Cowl 7

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.98	2.47	2.94	3.88	4.90
0.08	1.116	1.009	0.909	0.773	0.726
.12	.968	.877	.783	.649	.625
.16	.875	.782	.685	.582	.548
.22	.713	.633	.539	.499	.459
.28	.596	.535	.480	.400	.388
.36	.486	.438	.390	.334	.316
.44	.424	.384	.325	.288	.269
.54	.343	.299	.249	.241	.221
.64	.276	.251	.224	.187	.180
.76	.194	.172	.160	.143	.138
.88	.128	.125	.101	.107	.102
1.00	.080	.081	.067	.073	.078
1.12	.035	.043	.063	.056	.055
1.26	.011	.027	.028	.035	.043
1.40	-.009	.008	.014	.026	.031

Cowl 8

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.98	2.47	2.94	3.88	4.90
0.08	1.230	1.103	0.995	0.85[illegible]	0.793
.12	1.126	1.011	.922	.77[illegible]	.739
.16	1.013	.897	.804	.71[illegible]	.680
.22	.902	.802	.698	.64[illegible]	.596
.28	.823	.738	.690	.57[illegible]	.549
.36	.737	.659	.613	.51[illegible]	.495
.44	.620	.564	.509	.44[illegible]	.430
.54	.534	.478	.422	.39[illegible]	.361
.64	.482	.440	.411	.33[illegible]	.323
.76	.410	.367	.343	.26[illegible]	.275
.90	.324	.297	.263	.23[illegible]	.227
1.08	.254	.233	.203	.19[illegible]	.180
1.24	.203	.196	.181	.14[illegible]	.144
1.42	.145	.142	.138	.11[illegible]	.120
1.62	.090	.092	.083	.06[illegible]	.085
1.92	.038	.050	.050	.05[illegible]	.055
2.42	-.031	-.007	.009	.01[illegible]	.025

Cowl 9

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -				
	1.90	2.47	2.94	3.88	4.90
0.08	1.226	1.074	0.939	0.799	0.766
.11	1.116	.973	.871	.733	.706
.16	1.051	.897	.789	.691	.664
.22	.973	.846	.734	.668	.634
.30	.903	.836	.748	.639	.622
.38	.819	.783	.712	.606	.610
.48	.723	.707	.635	.553	.539
.60	.552	.567	.498	.467	.443
.74	.485	.497	.460	.397	.384
.90	.400	.425	.391	.334	.324
1.08	.327	.349	.309	.282	.270
1.30	.252	.279	.241	.231	.216
1.55	.202	.238	.213	.186	.181
1.90	.128	.168	.154	.135	.139
2.25	.050	.095	.087	.092	.097
2.60	-.001	.094	.052	.063	.067
2.95	-.039	.024	.031	.033	.049
3.25	-.057	-.003	-.001	.017	.038
3.60	-.081	-.016	-.006	.012	.025

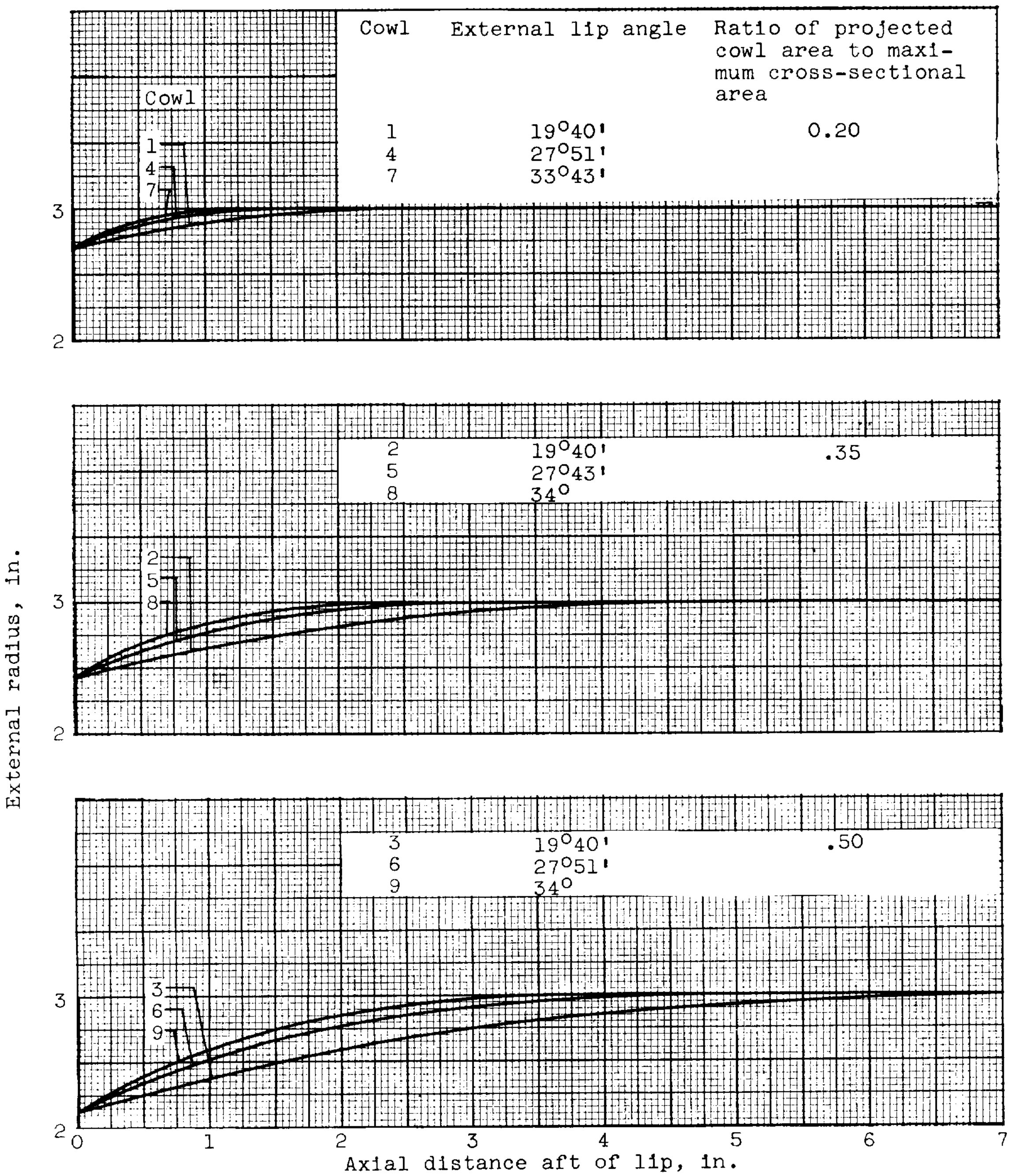
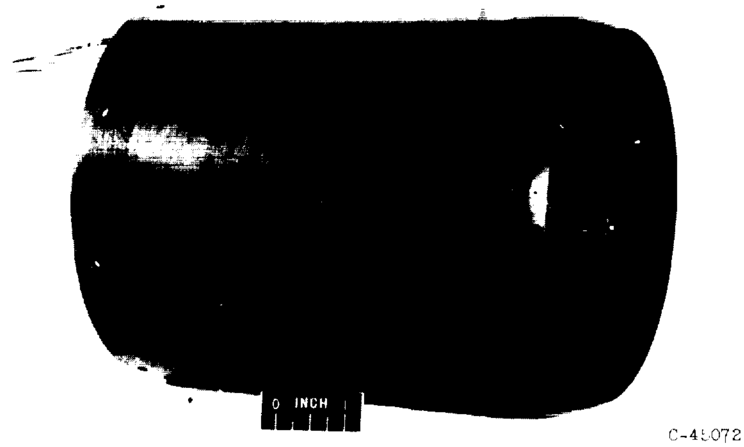
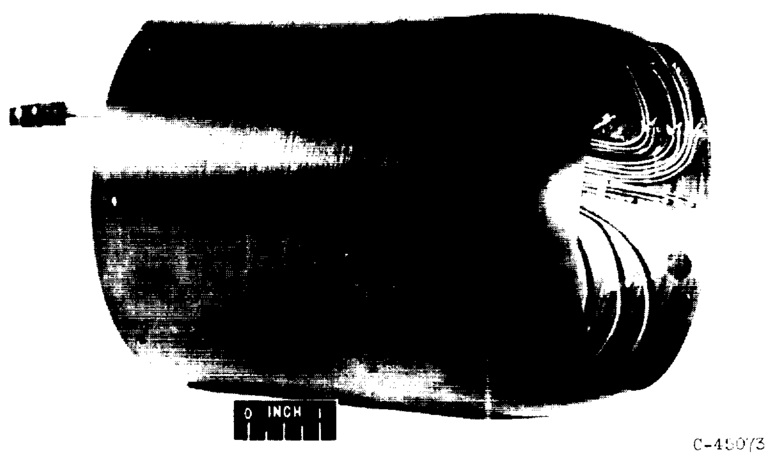


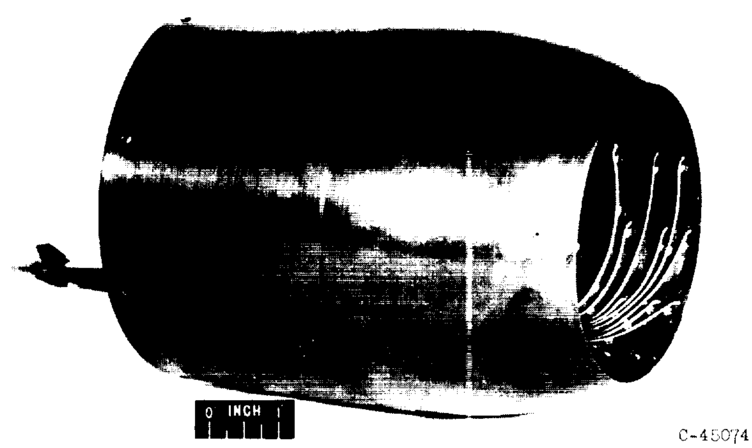
Figure 1. - Scale drawings of cowls.



(a) Cowl 7.



(b) Cowl 8.



(c) Cowl 9.

Figure 2. - Cowls 7, 8, and 9.

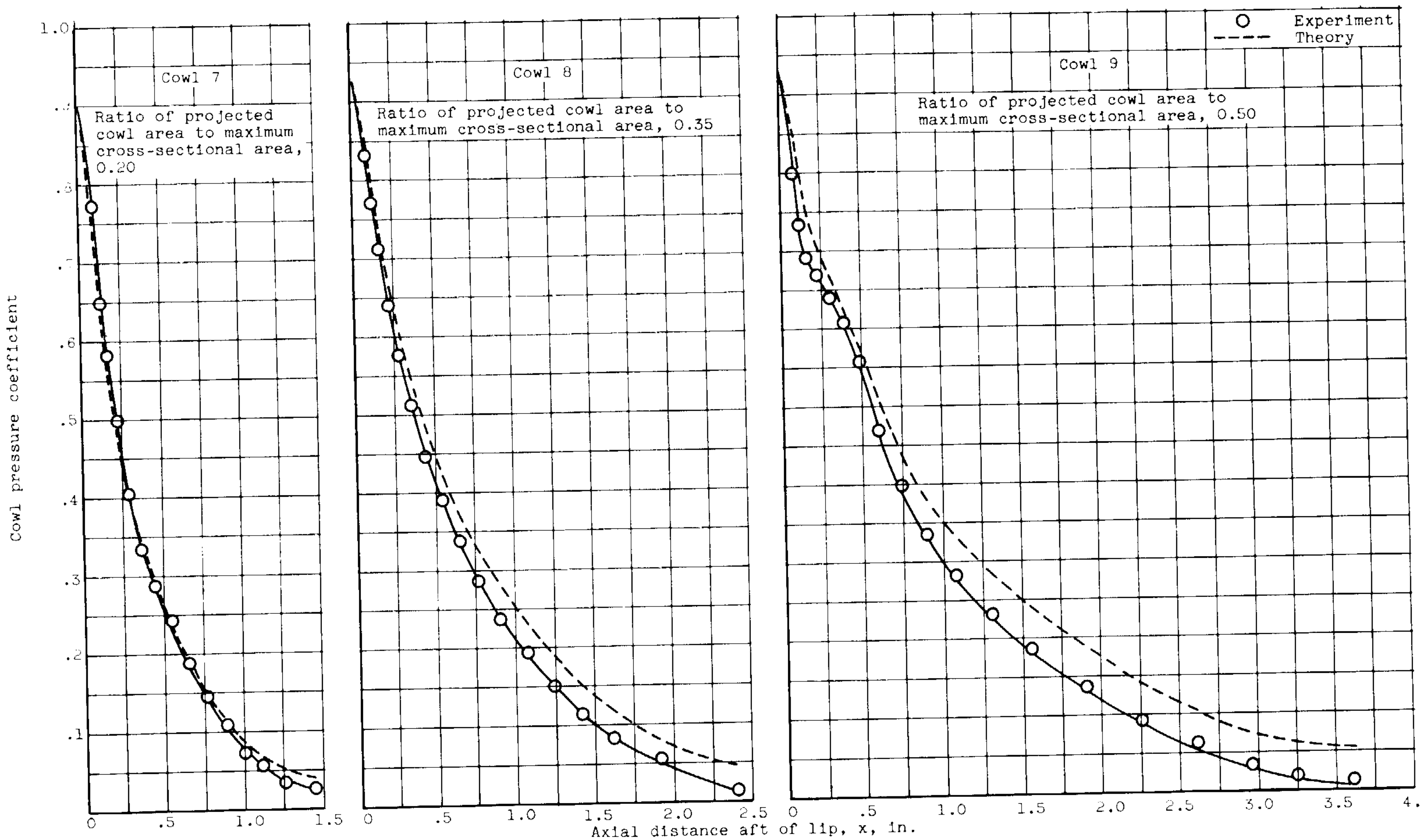
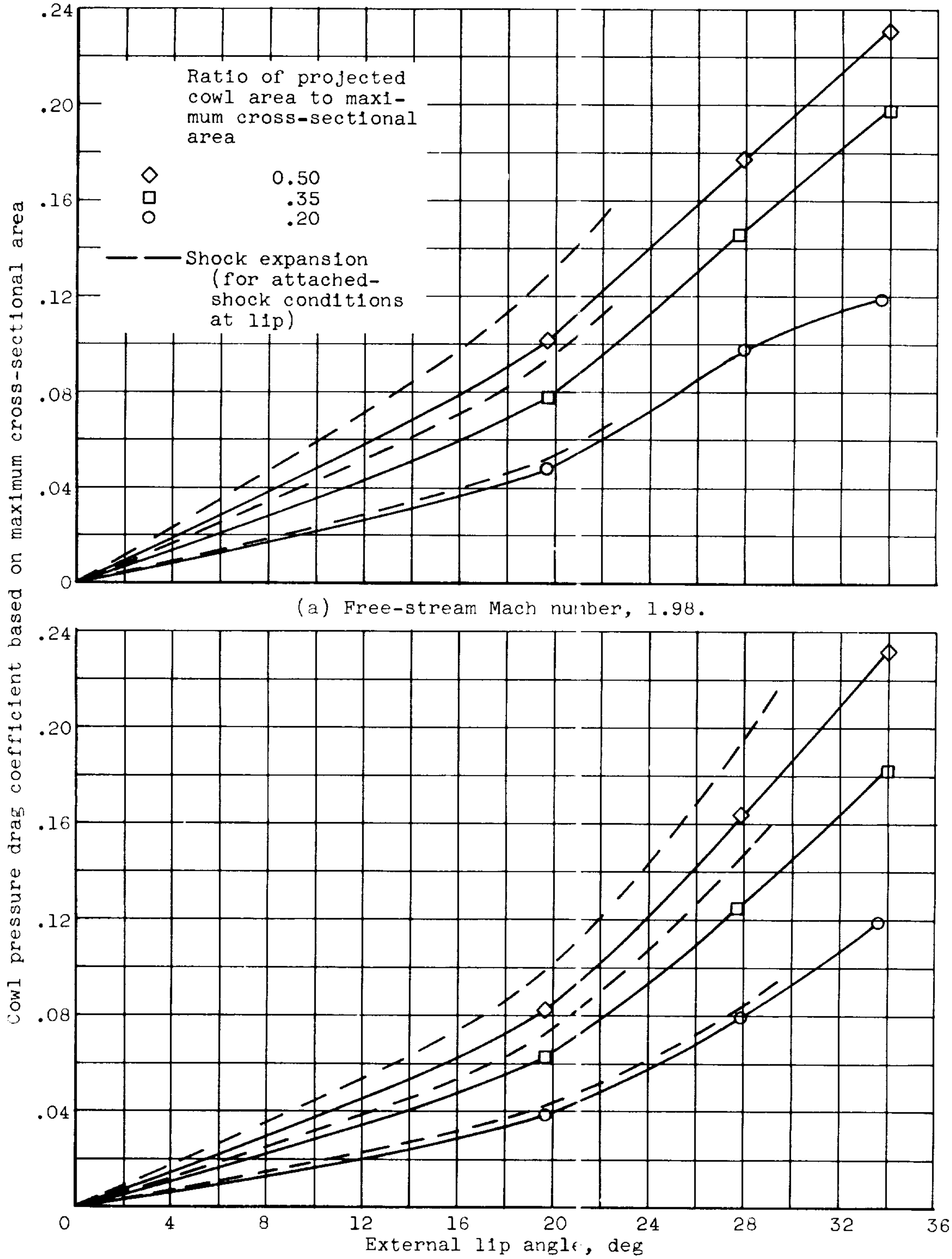
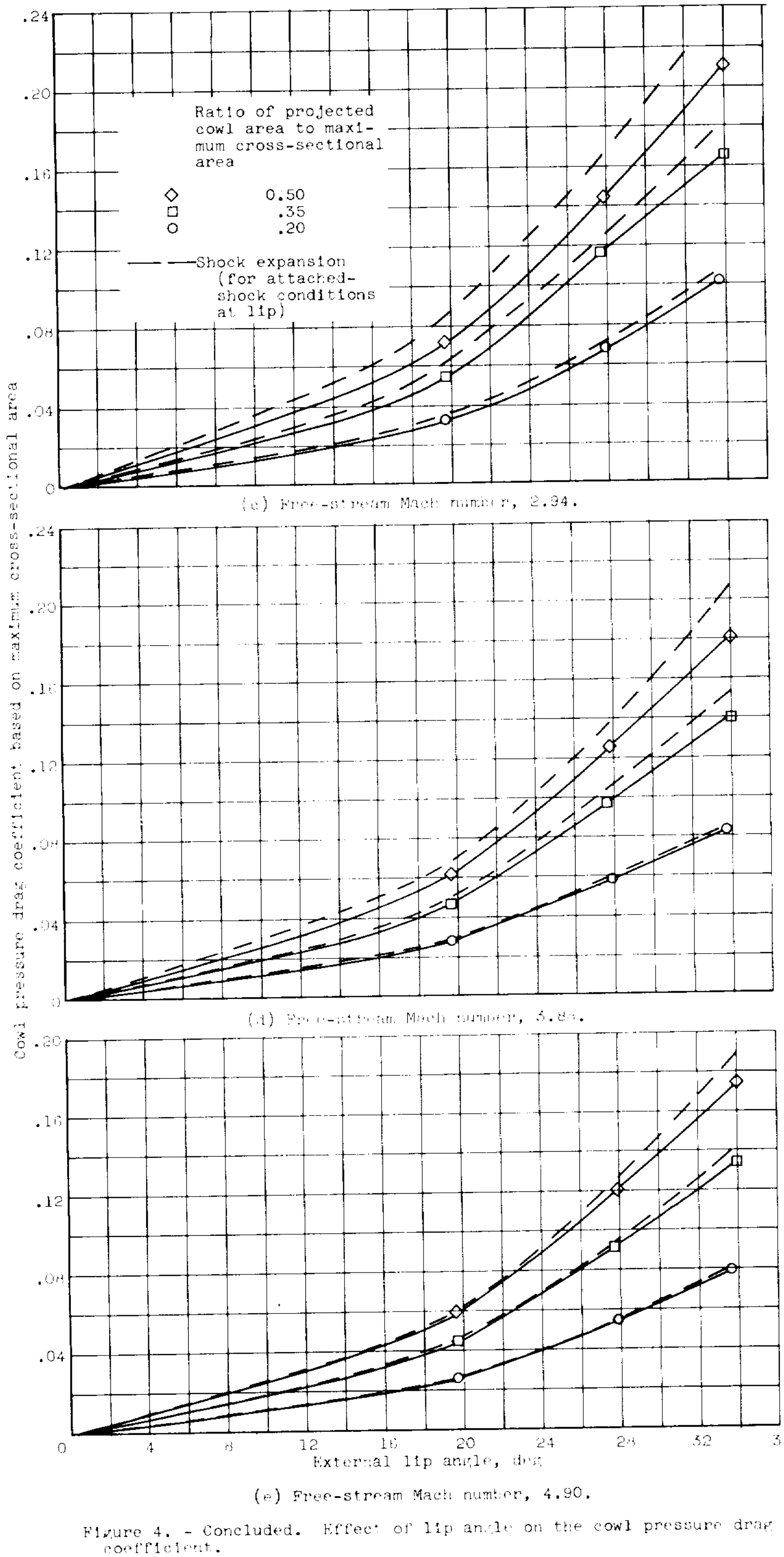


Figure 3. - Comparison of experimental and theoretical cowl pressure distributions. External lip angle, 34°; free-stream Mach number, 3.88.



(b) Free-stream Mach number, 2.47.

Figure 4. - Effect of lip angle on cowl pressure drag coefficient.



(c) Free-stream Mach number, 2.94.

(d) Free-stream Mach number, 3.85.

(e) Free-stream Mach number, 4.90.

Figure 4. - Concluded. Effect of lip angle on the cowl pressure drag coefficient.

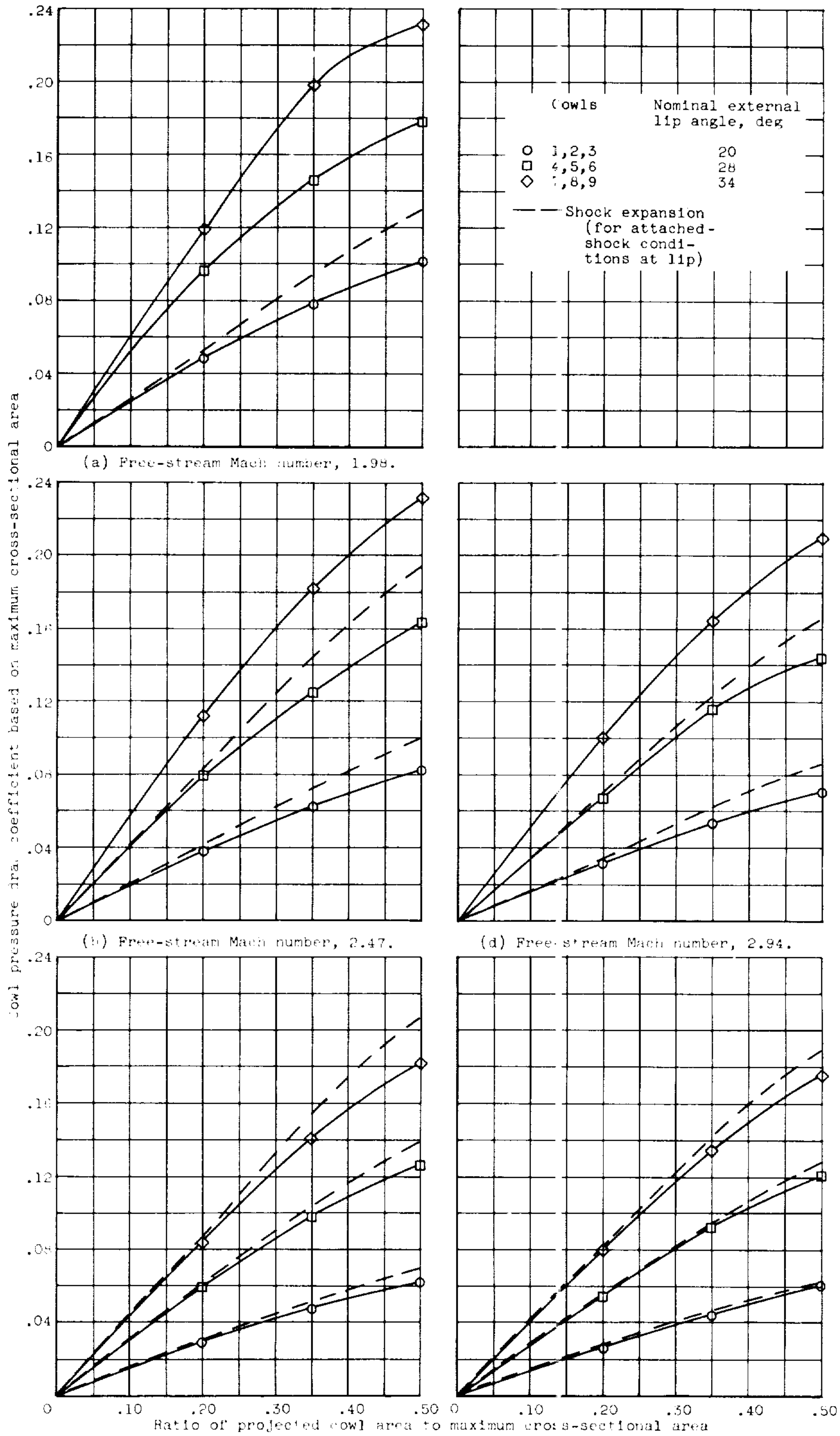
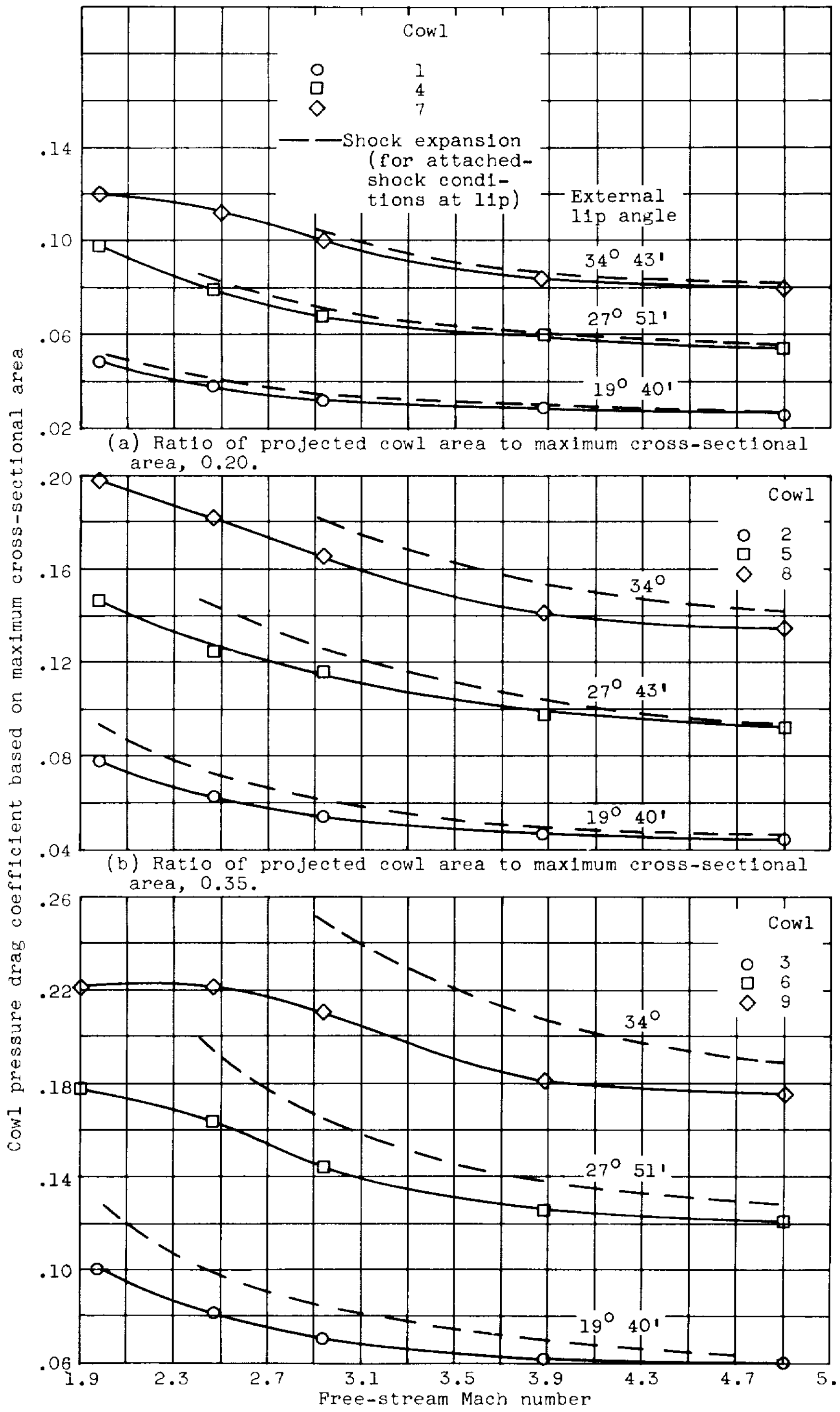


Figure 5. - Effect of projected cowl area on the cowl pressure drag coefficient.

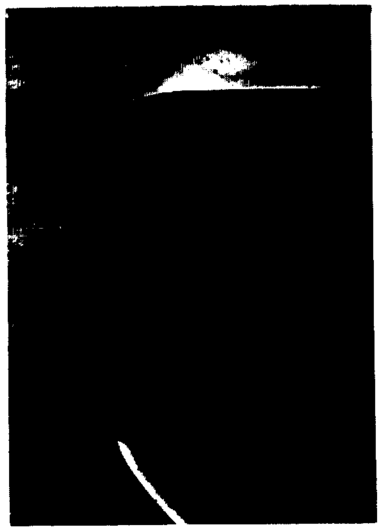


(a) Ratio of projected cowl area to maximum cross-sectional area, 0.20.

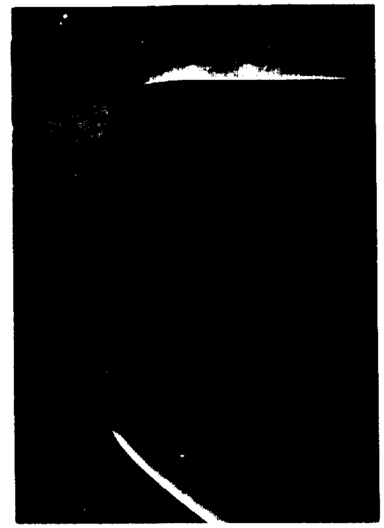
(b) Ratio of projected cowl area to maximum cross-sectional area, 0.35.

(c) Ratio of projected cowl area to maximum cross-sectional area, 0.50.

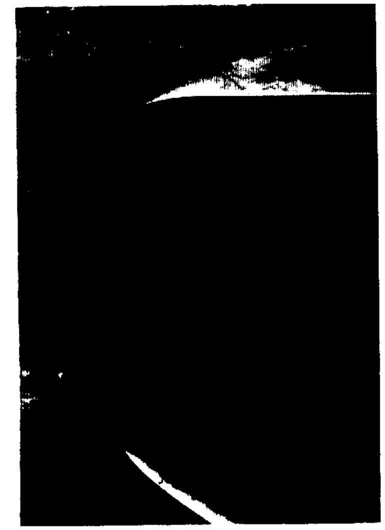
Figure 6. - Effect of Mach number on cowl pressure drag coefficient.



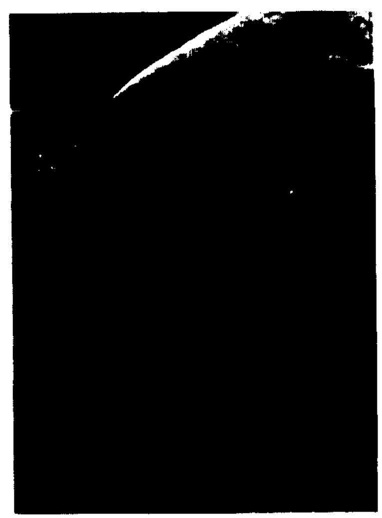
(a) Free-stream Mach number, 1.98



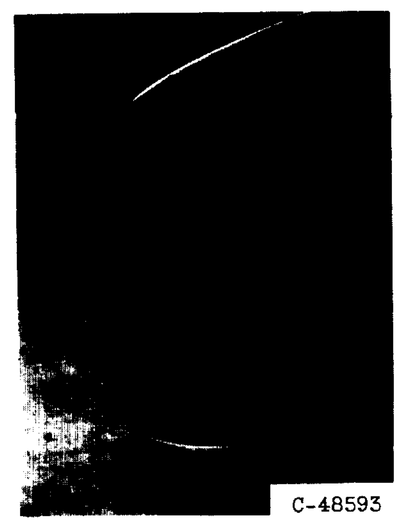
(b) Free-stream Mach number, 2.47.



(c) Free-stream Mach number, 2.94.



(d) Free-stream Mach number, 3.88.



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(e) Free-stream Mach number, 4.90.

Figure 7. - Schlieren photographs of cowl 7.

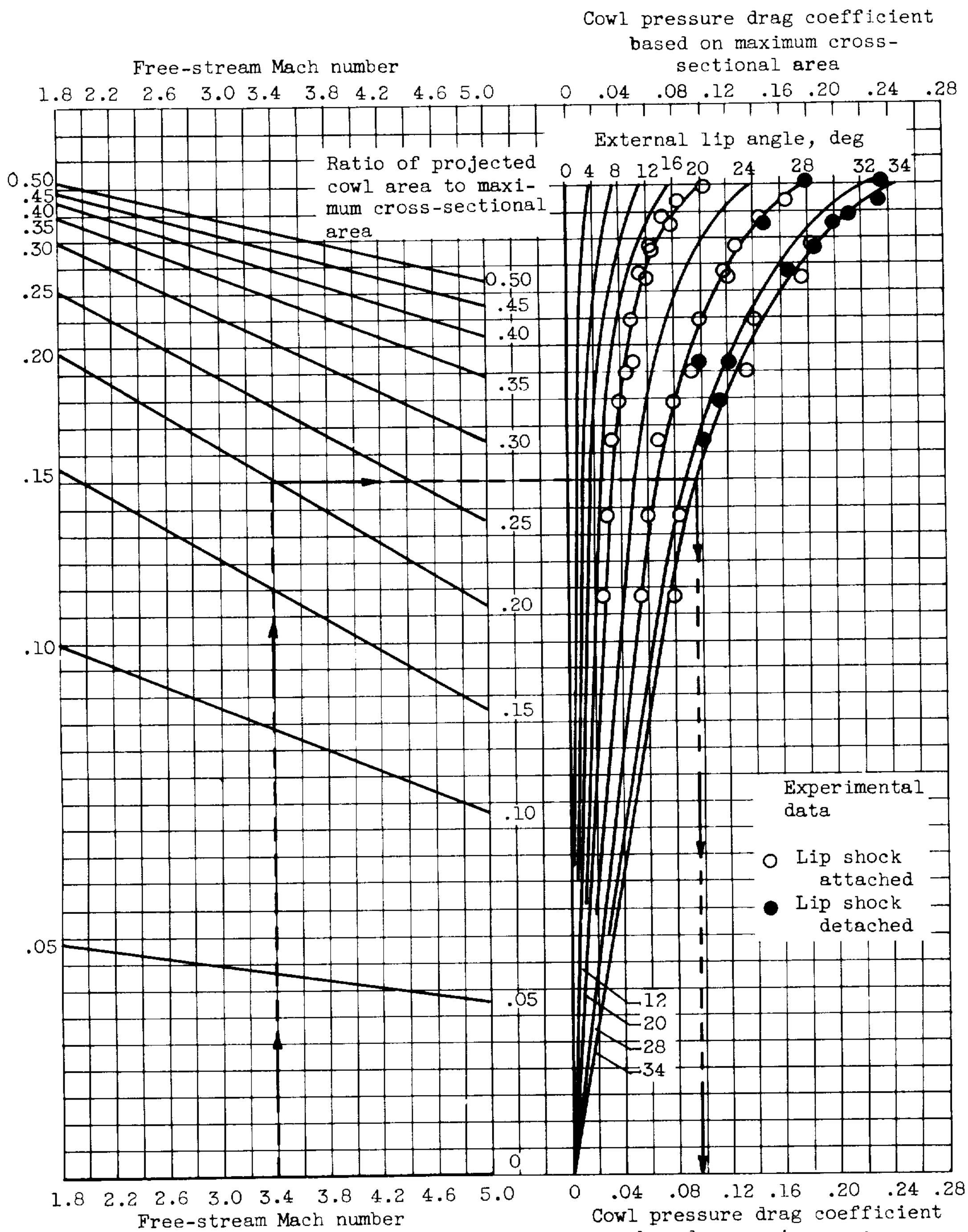

Figure 8. - Empirical chart for estimating cowl pressure drag coefficients of cowls approaching an elliptic contour. The pressure drag at a Mach number of 3.4 of a cowl having a ratio of projected area to maximum frontal area of 0.20 and an initial external lip angle of 34° is found by tracing the arrows to be approximately 0.096.